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Model Development with Verification for Thermal Analysis of Torsional Vibration Dampers

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Abstract. The crankshaft of aircraft's piston engine is exposed to harmful torsional vibration. If the oscillation reaches high value of amplitude fatigue damage of the propeller system occurs. To avoid this, torsional vibration damper can be mounted onto the free-end of the crankshaft. Visco-dampers are the simplest in structure but one of the most effective type of torsional vibration dampers, which have working fluid of silicone oil. Silicone oil is a non-Newtonian fluid and the highest effect on its lifetime is the temperature. Due to the thermal complexity of the structure and due to the lack of proper thermal measurement technology, it is a challenging task to perform thermal management of the damper especially based on purely analytical way. Numerical methods must be applied in design and development phase of the product to approximate the temperature field for lifetime calculation. A finite-difference-method based 2D thermal calculation procedure has been developed in MATLAB environment in order to reveal the hidden heat transfer processes among the damper components and to approximate the temperature distribution inside the structure with especial care for the silicone oil. The accuracy of the developed thermal model has been verified by a finite-volume-method based engineering software in ANSYS environment. The newly developed and verified thermal model has been used to update the Iwamoto-equation for providing more accurate outer surface temperature for the recently investigated damper housing in analytical way.

INTRODUCTION

The torsional vibration of aircrafts' propeller systems and the fatigue damage of the crankshaft have been a prominent problem since before the World War I. In early aircraft designs the engine life was so extremely short, that the torsional oscillations arising on the crankshafts could not be recognized, well understood and properly controlled. Designers explained the broken crankshaft with the fact, that the damaged engine component was not sized properly for the desired amount of torque to carry based only on gas pressure and inertia force calculations. The vibratory loads were totally neglected.

Torsional Vibration Problem of Aircrafts' Propeller System

Nowadays, it is well known that in case the frequency of the unwanted oscillations in the propeller system coincides with the natural torsional frequency of the crankshaft design, torsional resonance will occur, the shaft will suffer from fatigue damage, propeller blades will be lost, accessories will be sheared and gear trains will be stripped. Out of the resonance, the amplitude of the torsional vibration over the given limit can cause fatigue damage also. [1] Several factors can be identified as the sources of torsional oscillations in an aircraft engine such us the rotating propeller itself and the practice of shortening of blades, the electromechanical interaction between the electrical power system and the aircraft's drivetrain, the intermittent combustion and unbalanced inertial forces of the crankshaft or the usage of conversed automotive engine in aircrafts. Different methods are available to mitigate and eliminate the mentioned vibration problems of airplanes driven by piston engines. The use of wood and composite (glass fiber

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reinforced plastic) propellers, instead of metal-blade propellers (which are perfect springs with very little inherent damping), allow high degree of internal damping. Pendulum absorbers with counterweights have been developed to attenuate a particular order of vibration in dynamical way. Contrary to the absorbers, pure damper (see Fig. 1a) is more effective in reducing the vibration amplitude at any frequency, however, overheating and lifetime reduction of the damping structure is a design task since the damping energy is dissipated in form of heat. [2]

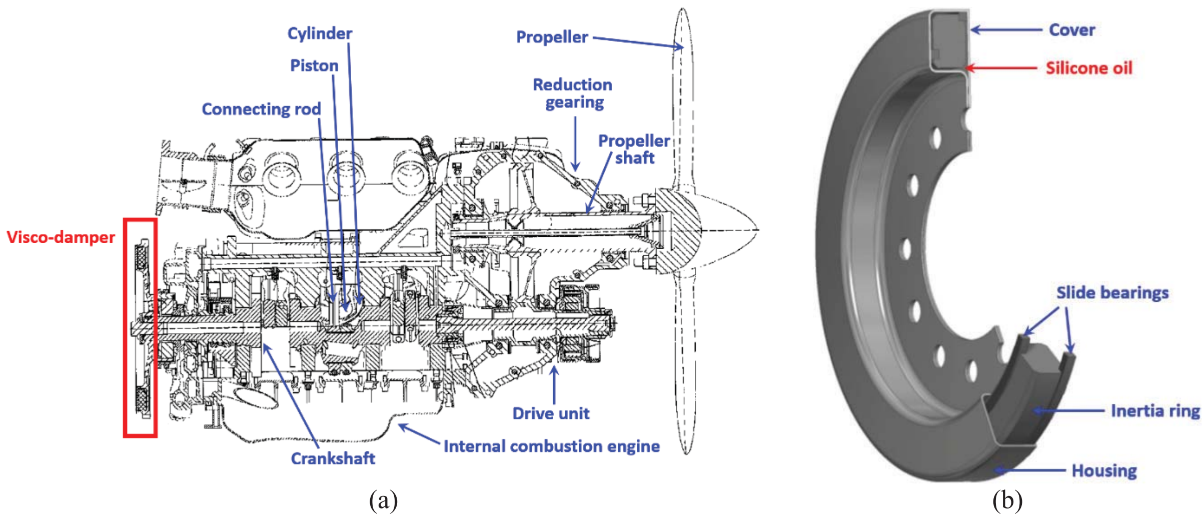


FIGURE 1. Visco-damper on the free-end of an aircraft's crankshaft (a) and the structure of a visco-damper (b) [3] [4]

Viscous Torsional Vibration Dampers

Viscous torsional vibration damper, or shortly visco-damper, is the simplest in structure but one of the most effective types of vibration dampers. According to Fig. 1b, the main parts of this damping product are the following: an annular space (called housing) includes the inertia ring with slide bearings and the damping fluid. A plate (called cover) is welded to the housing to make the annular space closed. Visco-dampers are spread all over the world considering general purpose applications not only in aircraft engines but also in heavy duty piston engines of military, architectural, agricultural and mining areas. Due to their simplicity and low maintenance, they are often used also in sports cars, trucks and ships. [4]

Silicone oil, as a non-Newtonian fluid, is used for damping medium in these products. During the operation, the oil is exposed to high thermal and mechanical loads. The generated temperature field has the highest effect on the lifetime of the silicone oil, which determines the operating time of the whole damper structure. [5]

The one of the most reasonable and effective solutions in design and development phases of the visco-dampers is to establish, use and necessarily improve calculation methods. Significant amount of time, capacity and cost can be saved by applying different numerical and analytical methods. However, the measurement-based validation is an indispensable step of introducing new calculation methodologies, which procedure will be the next steps of the present work.

SOLVING THE DAMPER THERMAL PROBLEM IN NUMERICAL WAY

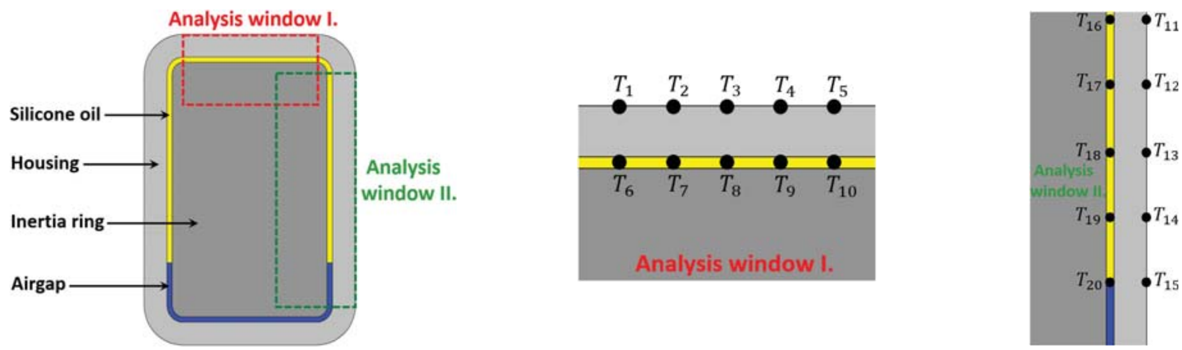
The one of the main goals of this paper, besides providing insight into the structure, operation and thermal problem of visco-dampers, is to develop a reliable 2D numerical method based thermal calculation model, which is suitable for estimating the temperature distribution in the damper components. Finite-difference-method has been used for the model development considering its advantages as one of quickest methods for solving differential equations: can be parallelized with high number of nodal distributions, easy to reach higher order spatial accuracy and implement in computer programs.

The principle of the selected numerical method is based on the application of a local Taylor expansion to approximate the partial differential equations. Regular, structured and fine mesh is required, formed by square network of lines, to construct properly the discretization of the partial differential equations.

Model Development for Thermal Analysis

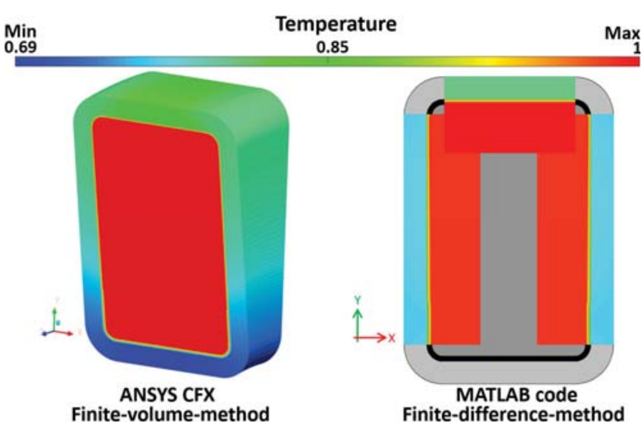
The applied thermal equations used in the model are derived from the general differential equation of heat conduction and from the differential equation of Fourier's Law. The heat dissipation due to the damping mechanism is considered as nodal heat source in the function of radius. Interface connections on the material borders are considered as type-four ideal contacts. The radius-dependent heat transfer coefficient on the outer surface of the housing is calculated by an empirical formula. The script of the developed thermal calculation model is written in MATLAB environment and does not need any special skills of damper experts or material scientists to use. The model requires geometrical data, operational boundary conditions and material properties of the investigated visco-damper product and calculates the temperature field for each component in analysis windows defined in a 2D simplified damper cross-section by approximating the hidden heat transfer processes among the inertia ring, silicone oil film, housing and the ambient.

The finite-difference-method based calculation was carried out on a uniform, squares-structured mesh. The silicone oil gap has been divided into 20 sublayers. Two analysis windows (I. and II. marked by dashed lines in Fig. 2a) have been defined in the cross-section of the simplified damper geometry. In each analysis window five verification points have been taken equidistantly in the silicone oil gap and on the outer surface of the housing (see Fig. 2b).



(a) (b)

FIGURE 2. Simplified 2D visco-damper geometry for numerical analyses (a) with verification points (b)



(a) (b)

FIGURE 3. Comparison of numerical results calculated by finite-volume (a) and finite-difference method (b)

Verification of the Thermal Model

The accuracy of the developed thermal model has been investigated by a finite-volume-method based advanced engineering software in ANSYS environment. ANSYS is a general-purpose software, used to simulate standalone cases and interactions of physics as structural, vibration, fluid dynamics, heat transfer and electromagnetics for engineers. A 3D segment (segment angle is 10° as shown in Fig. 3a) of the whole damper geometry has been used for verification in ANSYS CFX submodule.

It turned out from the comparison of the results (see Fig. 3a and 3b), that in case of analysis window I. the highest relative deviation in oil temperatures (in verification points 6 – 10) is 8.96% and this value is 6.69% in case of housing surface temperatures (in verification points 1 - 5). As far as the numerical results of analysis window II. is concerned, the highest relative deviation in the oil (in verification points 16 - 20) is 7.73% while this value is 5.45% on the outer surface of the housing (in verification points 11 - 15). In each verification point the relative deviation is below 10%.

As the presently introduced model is considered to be the first step of a design tool developments, the calculation method is acceptable under the investigated conditions. By performing further developments on the presented 2D damper thermal model, an advanced pre-design tool will be available in the future to estimate the temperature distribution and the operational time of the whole damping structure with acceptable accuracy and without expensive prototyping, risky thermal and performance measurements and any need for advanced engineering software.

Updating Iwamoto-Equation

A half empirical analytical expression (Eq. 1), developed by S. Iwamoto, is available and can be used for preliminary thermal analysis of viscous torsional vibration dampers to estimate the outer surface temperature of the damper housing under operation [6]:

$$\dot{Q} = 112.1 \cdot a \cdot \omega^{0.8} \cdot A^{1.3} \cdot (T_s - T_{amb}) \cdot e^{-0.00176 \cdot T_s}, \quad (1)$$

where $\dot{Q}$ is the total damping power or dissipated heat per unit time [W], a is the geometry-dependent Iwamoto-coefficient, ω is the angular velocity of the housing [rad/s], A is the outer surface of the housing [m^2], T_s is the outer surface temperature of the housing [°C] and T_{amb} is the ambient temperature [°C].

The above presented Iwamoto-equation (Eq. 1) is considered a transcendental equation as there is no closed-form solution for expressing variable T_s. After substituting the known values (damping power, Iwamoto-coefficient, angular velocity, outer surface and ambient temperature), a root-finding algorithm has been used to obtain the unknown T_s value. The equation has been tested on three different, simplified visco-damper geometries and found to provide different results than the numerical investigations, thus the equation has been updated with help of the numerical results by parameter identification.

CONCLUSION

A finite-difference-method based thermal calculation model has been developed to estimate the temperature distribution in a 2D simplified visco-damper geometry with special care for the silicone oil. The model has been verified by ANSYS CFX software and the highest relative deviation in verification points remain under 10%. The thermal analysis has been used to update the original Iwamoto-equation in order to provide more accurate housing outer surface temperature in analytical way.

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